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PHYSIOLOGICAL REVIEW

Sleep, circadian rhythms, and athletic performance

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SUMMARY

Sleep deprivation and time of day are both known to influence performance. A growing body of research has focused on how sleep and circadian rhythms impact athletic performance. This review provides a systematic overview of this research. We searched three different databases for articles on these issues and inspected relevant reference lists. In all, 113 articles met our inclusion criteria. The most robust result is that athletic performance seems to be best in the evening around the time when the core body temperature typically is at its peak. Sleep deprivation was negatively associated with performance whereas sleep extension seems to improve performance. The effects of desynchronization of circadian rhythms depend on the local time at which performance occurs. The review includes a discussion of differences regarding types of skills involved as well as methodological issues.

Introduction

The impact of sleep deprivation, disruption of circadian rhythm, and time of day on athletic performance has been extensively investigated, but a systematic overview is still lacking. Circadian rhythms are seen in the sleep–wake cycle as well as in several other aspects of human functioning. These rhythms are generated by the suprachiasmatic nuclei. The period of the endogenous rhythms is somewhat longer than 24 h [1]. However, the circadian rhythms are also influenced by external cues (zeitgebers) which normally entrain the endogenous rhythms to a 24-h rhythm [2], thereby preventing them from "free-running". There are individual differences in the phase of circadian entrainment (i.e., morningness–eveningness dimension). Morning types have an advanced rhythm (early bed and rise times) and evening types display a delayed rhythm (late bed and rise times), compared to intermediate types [3].

According to the two-process model of sleep regulation, humans' tendency to sleep is determined by the time passed since the last sleep episode (homeostatic factor) as well as by time of day (circadian factor) [4]. The homeostatic factor is evident in humans' rising need for sleep after sustained wakefulness, while the circadian factor is evident in the increasing sleep propensity that normally occurs during the dark part of the 24-h d.

Studies have taken different approaches in investigating how sleep deprivation and circadian disruption affect athletic performance. Some studies have focused on physiological measures, while others assess athletic performance. Furthermore, sports differ greatly as to which skills are important for successful performance [2]. The focus of the present review concerns the impact of sleep and circadian rhythms in studies utilizing direct measures of athletic performance, which are arguably more relevant to real sports competitions than are physiological responses to exercise (e.g., heart rate and oxygen uptake) [5].

Methods

We searched the databases ISI Web of Science, PubMed and PsycInfo for articles using each of the following words: *Chrono**, *diurnal*, *morningness*, *eveningness*, *morning type**, *evening type**, and

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*circad**, in combination with each of the words: *Athletic*, *performance,* and *sport**. The inclusion criteria were *peer reviewed journal articles* written *in English* and published between 1980 and 2012, reporting data of *objective measures* of *athletic performance* (e.g., times, scores etc.). Studies were excluded if they exclusively reported: *a)* physiological responses to exercise, *b)* subjective measures of sport performance, *c)* sports involving minimal physical performance (e.g., shooting, darts, driving), *d)* simple tests of reaction time, grip strength, flexibility and balance, *e)* case studies and studies in children, *f)* studies in the effect of medication or stimulants on performance, *g)* studies in eumenorrheic women or on effects of menstrual cycles on performance, and *h)* studies conducted in settings where the effect of sleep deprivation cannot be distinguished from the effect of training or fatigue (e.g., expeditions, extreme competitions lasting several days, military training operations). The search yielded a total of 3726 records, including duplicates. After selecting relevant articles, we examined their reference lists for additional studies that met our inclusion criteria. A total of 113 articles were included.

We hypothesized that the overall findings from these studies would indicate that sleep deprivation and desynchronization of circadian rhythms negatively affect performance and that performances display a diurnal variation, being better in the evening than in the morning.

Results – sleep loss

Total sleep deprivation

Anaerobic performance is often examined using procedures involving subjects' performance on ergometer cycles, such as the Wingate anaerobic power test or force-velocity tests. Intensity is high and duration of performance is short: the Wingate test typically involves 30-s or 60-s effort, while the Force-velocity test includes several 6-s sprints. Research indicates that total sleep deprivation is not detrimental to performance on these tests. No effect on Wingate performance was found after one night of sleep deprivation [6,7], after 48 h [8], or even after 60 h of sleep deprivation [9]. A night of total sleep deprivation, however, was found to decrease evening performance, possibly through attenuation of the normal rise in performance during evening hours due to cumulative fatigue [7]. Another study reported no effect of one night of sleep deprivation on total work done or time to exhaustion in an intensive all-out cycling exercise [10].

Several studies have found that muscle strength is unaffected by sleep deprivation. A 24-h sleep deprivation had no effect on performance on the snatch, clean and jerk, or front squat [11]; 36 h of sleep deprivation had no effect on elbow flexion or extension strength [12], and 60 h of sleep deprivation did not decrease maximal strength and endurance of either upper or lower body muscle groups [9,13]. One night of sleep deprivation had no significant effect on back or leg strength the following day, but back strength was reduced after a night of recovery sleep [14]. Knee flexion torque was unaffected after 30 h of sleep deprivation [15] and after 64 h [16]. Knee extension torque, however, decreased after 30 h of sleep deprivation [15], and after 64 h of sleep deprivation, although only at a low speed of rotation [16]. Endurance of knee extensors and flexors was unaffected after 64 h of sleep deprivation, as were running times for the 40-m dash, while there was a decrease in vertical jump height [16]. The two latter studies did not include appropriate control groups.

In sum, these results suggest that tasks requiring short-term high-power output are largely unaffected by one or several nights of sleep deprivation. One of the mechanisms by which sleep deprivation may affect performance is reduced motivation [7,9,11]. Although these tasks all require motivation [9], they demand that motivation is sustained only for a short time, thus making performance viable even with an accumulated sleep debt.

Regarding performance of a longer duration, one study found that mean sprint performance and performance on repeated deep-squats during a 50-min exercise protocol was reduced after 30 h of sleep deprivation, as was knee extensor strength measured after the 50-min protocol. Total distance covered during the submaximal exercise part of the protocol was not significantly altered, but distance during the first and last 10 min of the submaximal exercise was reduced [17]. Other studies reported that one night of sleep deprivation reduced the total distance covered during treadmill walking [18], while 42 h of sleep deprivation reduced time to exhaustion in ergometer cycling [19], and sleep deprivation for 36 h [20] and 50 h [21] reduced time to exhaustion on treadmill walking. The tests were conducted in the morning or afternoon in at least three of these studies [17,18,21]. Thus, sleep deprivation appears to affect endurance performance. The participants may be less motivated to endure discomfort after sleep deprivation [22]. In addition, sleep deprivation may lead to changes in perception of effort. Ratings of perceived exertion either remained unchanged or increased after sleep deprivation, although actual performance decreased [17–20]. Physiological effects (e.g., changes in cardiovascular, respiratory, and metabolic variables) were negligible in these studies [17–22]. On the other hand, 60 h of sleep deprivation did not significantly affect time to exhaustion in ergometer cycling [23]. The subjects in this study were all women and the task was ergometer cycling rather than treadmill walking, thus, less muscle mass was activated; the subjects were also kept awake by various cognitive tests throughout the sleepless period [23]. Another possible explanation of the divergent results may be the relatively short performance session in this study as compared with the majority of the other studies [17,18,20,21] (19 min vs. 30 min or more).

Partial sleep deprivation

Depriving subjects of sleep in the beginning of the night by delaying bedtime until 03:00 h has been found not to affect performance on the 30-s Wingate test [6,24,25]. However, depriving subjects of sleep at the end of the night had a negative impact, although only on performance in the evening, possibly due to a decrease in the circadian rhythm amplitude and/or due to increased fatigue caused by staying awake for a longer period of time [25].

Restricting subjects' sleep to 2.5–3 h per night (allowed at the end of the night) for three successive days affected neither standing broad jump performance or time to exhaustion on a treadmill [26], nor maximal biceps curl [27]. However, performance on maximal bench press, leg press, and dead lift decreased [27]. The authors noted that these tasks require activation of larger muscle groups than the biceps curl, that the latter tasks were more affected than the first ones, and that a decline in motivation was most likely involved [27]. The performance tests in the latter studies [25–27] were conducted in the evening, while the studies that found no effect of total sleep deprivation on similar measures conducted the tests in the morning or afternoon [9,11,13,15]. All in all these results may indicate an interaction between sleep deprivation and time of day on performance, which is a topic that should receive more attention in future studies. In a study on shift workers recovering from a week of night shifts, endurance time on ergometer cycling decreased, although only the times of the older workers [22]. It is likely that the participants both had experienced a week of partial sleep deprivation and had a delayed circadian phase at the time of testing as a consequence of the night work. The cycling session

lasted less than 15 min, which is shorter than in the other studies reporting significant effects of sleep deprivation on endurance performance. Poorer sleep or poorer adjustment to night work are possible causes for the decrease in performance affecting the older workers, however, the specific mechanisms are not clear [22]. Furthermore, a 30-min nap in the afternoon after a night of partial sleep deprivation (wake time at 03:00 h), was found to improve performances on 2-m and 20-m sprints, compared to a no-nap condition [28]. By reducing the fatigue caused by the sleep loss, the nap may have enhanced readiness and motivation to perform [2,28].

Extended sleep duration

Most of the research considering sleep and athletic performance has focused on the effect of sleep deprivation. However, one study has investigated the effect of extended sleep on performance. After a baseline period of habitual sleep durations, the subjects slept as much as possible over a period of five–seven weeks. Increasing the total amount of sleep time resulted in improved times on 282-foot sprints, and increased free throw and 3-point shooting accuracy with a basketball [29]. The subjects in this study were collegiate athletes who carried a certain sleep debt. In line with the finding that naps increase performance, the extended sleep may have had an impact by reducing fatigue [29]. There were, however, some major methodological limitations in this study, notably the lack of a control group, and thus findings should be interpreted with caution.

Results – time of day

Technical skills

The accuracy of short and long badminton serves was found to be higher in the afternoon than in the morning and evening, while consistency of the serves did not vary significantly across the day [30]. Accuracy of first serves in tennis was better in the morning and afternoon than in the evening, while speed was higher in the evening than in the morning. Second serves did not display a diurnal variation in accuracy or speed [31].

Regarding swimming, a decrease in stroke length and an increase in stroke rate from morning to evening are reported. The first forward movement of the hand under water, as well as the maximal depth, was higher in the evening than in the morning, while the backward movement of the hand was unaffected by time of day. The 50-m swimming velocity was higher in the evening than in the morning and afternoon [32].

Studies of soccer skills have reported that juggling is better in the afternoon [33], while chipping is more accurate in the afternoon [33] or evening [34]. Better performances in the evening are also reported for the wall-volley test [33,34], the Yeagley soccer test [34], and dribbling speed [33,34]. No significant diurnal variation was found for penalty kicks [34].

Muscle strength and explosive leg power

Back strength has been reported to be better in the evening than in the morning [35,36]. Data on leg strength indicate a similar evening peak in performance [35,37], although in one study the evening peak was only present among the male subjects [38]. Studies also reported a diurnal variation in the torque of knee extensors, with better performance in the afternoon [39] or evening [40–45] both during submaximal exercise and during rest [46]. This is also found for contractions of the triceps surae [47]. For peak torque of knee extensors and total work done, higher afternoon or evening values became apparent only at a certain velocity [39,45]. Peak torque of knee flexors was found not to vary significantly according to time of day at any velocity [39,45], but acrophases were still noted in the afternoon [39]. Studies have reported better evening performance of both knee flexors and extensors, in addition to increased back strength [36]. After a period of training in the morning, the morning-to-evening increase in strength of knee extensors decreased or disappeared, while a period of training in the evening did not alter the diurnal variation in performance [48,49]. Diurnal variation in plantar flexion torque has been found to be dependent on the morningness–eveningness dimension: torque was higher in the evening than in the morning, particularly for the evening types. There was no diurnal variation in torque generation among the morning types [50].

Superior evening performance has been found on the standing broad jump test [51], the sergeant jump test [34], and in the drop jump [47] and countermovement jump [52,53], but not on the standing long jump test [34]. Maximal power elicited during a multi-jump test is reported to be higher in the afternoon than in the morning [54]. Force and power output of countermovement jump and the isometric mid-thigh pull have been found to present a clear circadian rhythm, with higher values at 16:00 h than in the morning and in the late evening [55]. For the squat jump there was a less clear circadian rhythm, where only the values in the morning were significantly lower [55]. Better performance in the evening has been reported for 20-m sprints [34].

In a study on athletes who were used to training both in the morning and evening, standing broad jump performance did not vary with time of day [56]. Increased warm-up in the morning, which raises the body temperature to evening levels, has been found to blunt the diurnal variation in countermovement jump [53]. Furthermore, studies conducted in warm environments found no diurnal variation in jump performance [57–59], power output [59] and strength of knee extensors [60], probably due to environmental-based, passive warm-up, enhancing morning performance as compared with evening performance [57–60].

Regarding upper body strength, the torque developed by elbow flexors has been found to have an acrophase around 18:00 h and a bathyphase in the early morning [61–64]. The eccentric strength of elbow flexors, unlike concentric strength, did not present this diurnal variation [65]. There was no diurnal variation in endurance or recovery of the elbow flexors [64]. One study reported that maximal triceps strength was better in the evening than in the morning for male subjects only [38].

Short term (anaerobic) performance

A higher maximum power on the force-velocity test is reported in the afternoon or evening compared to the morning [25,54,66–68]. Contrary to this, one study found that only the first sprint elicited higher performance in the evening than in the morning, while the following sprints and total work done were unaffected by time of day [69], and another study found no diurnal variation for any of the cycling parameters [70]. In sum, initial muscle power is higher in the evening than in the morning in a neutral environment, while repeated sprint ability may not be better [68,69], possibly due to the first sprint having a warm-up effect [69]. No diurnal variation in maximal power on the force-velocity test was found in a tropical environment, probably due to the passive warm-up caused by the environment and thus blunting the diurnal variation [57,58], and neither morning nor evening training produced any time-specific effects [58].

On a 15-s Wingate test, peak power, but not mean power, was higher in the evening than in the morning [71]. On the 30-s Wingate test, peak power and mean power are reported to be

higher in the afternoon [72–74] or evening [66,75–77] than in the morning, and total work done is also found to display higher values in the evening than in the morning [75,77]. A similar diurnal variation in anaerobic performance is also found for the 60-s Wingate test [78,79]. Studies which have measured Wingate test performance regularly throughout the day report a circadian rhythm in anaerobic power and capacity [72,77,80], with one exception [81]. Active warm-up was associated with less morning-to-evening increase in performance as compared with a shorter warm-up procedure, due to enhanced morning performance [74]. A morning-only exercise regime reduced the earlier observed diurnal variation in peak anaerobic power, while an evening-only exercise regime increased the evening values on this parameter [48].

Timing of sleep and meal schedules has been found to influence time for peak performance on 80-m sprints; peak performance occurred at 17:00 h on the day these schedules were advanced by two h, and at 21:00 h when schedules were delayed by two h. When only the sleep/wake schedule was advanced, but not the meal schedule, peak performance occurred at 19:00 h, similar to control days [82].

Morning-to-evening increases in mean and peak power have been found in performance on a swim bench [83]. Swimming speed has been reported to be slower in the morning than in the evening [84,85], even for swimmers accustomed to exercising in the morning [86]. Furthermore, this diurnal variation remained even with increased warm-up in the morning and decreased warm-up in the evening [87]. Four months of training both in the morning and in the evening, however, tended to decrease the superior evening performance observed before the training schedule among competitive swimmers [88].

Endurance (aerobic) performance

Time to exhaustion in ergometer cycling has been found to be greater in the evening than in the morning [89–91]; the same is reported for total work performed [92] and in time to exhaustion on a treadmill [93]. Evening superiority in power output and cycling time is found even in morning-type athletes who undergo a vigorous warm-up procedure before testing [94]. A circadian rhythm in performance with an acrophase in the late afternoon is found in time to exhaustion in an arm cycling exercise [95]. Other studies on endurance have not found time to exhaustion or power output variations based on time of day [96–99]. Possible explanations for this are small sample sizes [96,98,99], subjects' routine of training in the morning [96], a fatigue effect caused by two tests in the same day [97], and a long (>60 min) time-to-exhaustion session where a lower body temperature in the morning could be an advantage [98]. One study found that overall performance on a 60-min self-paced exercise did not vary according to time of day, but that performance was higher in the evening than in the morning for the first 30 min, while performance in the second half of the session was higher in the morning [100]. In an 80-min self-paced exercise, an effect of time of day was found for the young subjects only, who displayed higher work rates in the evening. Older subjects are generally more morning oriented, which may be a reason for the lack of evening superiority. For both age groups, work rates in the morning were stable, while work rates in the evening were very high during the first quarter of the session, and then decreased [101]. The observation in the two latter studies that initial effort during long evening sessions is very high but then slows down may reflect that the subjects reached a higher than optimal body temperature [100,101]. In line with this reasoning, time to exhaustion in a long cycling session which was conducted in a warm environment was greater in the morning than in the evening, and the authors noted that the lower initial body temperature in the morning probably allowed for a longer exercise time [102]. Time-specific training had no significant effect on morning-to-evening differences in time to exhaustion on an ergometer cycle [103], while in another study, the evening training group performed better on this test in the evening than in the morning, while the morning training group did not display this diurnal variation in performance, indicating that the time-specific training may have had an effect [104]. There were no reports on the subjects' circadian preferences in these studies, which may have contributed to the equivocal results. Among athletes accustomed to both morning and evening training sessions, performance in 2000-m ergometer rowing was better in the morning than in the evening for the group as a whole, while the intermediate and evening types showed no diurnal variation in rowing performance [56]. In other studies, no significant differences in endurance performance were found between morning, intermediate and evening types [93,97]. The latter studies were conducted on untrained individuals, while in the former study the subjects were highly trained athletes with high motivation for the assigned task [56]. It should also be noted that in the former study, the subjects rose very early and were probably sleep deprived [56], which may have contributed to their evening non-superiority.

Results – desynchronization of circadian rhythms

Travelling across several time zones often leads to jet lag. This implies that the traveller's internal clock is not synchronized with the local time [105]. Attending a competition at the local time often implies competing at a time the athletes' internal body clock is tuned to night-time [5]. Therefore, athletes travelling long distances often arrive a few days before the competition to allow for entrainment of their circadian rhythms to the new local time. It is acknowledged that it generally takes about one day per crossed time zone to adjust completely. Still, as the period of the endogenous rhythm for most people is somewhat longer than 24 h it is easier to delay than to advance the rhythm [106]. This implies that adjustment is normally faster when travelling westward than eastward.

For most regular competitions during the season, athletes' time schedules are often tight and often do not include enough time to adjust. Several approaches have been used to examine how circadian rhythms affect performance. One line of research takes advantage of archival data, typically examining the performance of teams from different time zones when they meet each other in competitions. American football teams travelling eastwards to visit their opponents were found to perform worse than teams travelling westwards (i.e., scored fewer points, had more points scored against them, and were beaten by higher margins) [107]. The same trend is noted in baseball, where US West Coast teams are at a disadvantage compared to their eastern US opponents who do not have to travel east preceding their away matches [108]. The disadvantage of travelling east for performance has also been found with reference to individual performances. After an eastward flight involving the crossing of eight time zones, peak and mean squat jump velocity and counter movement jump height decreased [109]. No significant effects were found for counter movement jump velocity or squat jump height. In another study involving eastward travel across eight time zones, 30-m sprint performance was not affected [110]. In both these studies, the testing occurred between 9:30 h and 11:00 h local time. There were only five subjects in the travel group, and they reported no decrease in motivation; both factors may have contributed to the insignificant results. After eastward travel across six time zones, there was a decline in strength and endurance of elbow flexors, and performance on the 270-m sprint, 2.8 km run and 110-m lift and carry task. The testing

was conducted at 7:30 h local time. Strength and endurance of knee extensors, and strength of the upper torso, legs, and trunk extensor muscles did not exhibit any change after travel, neither did performance on climbing a 6.5-m rope [111]. Eastward travel across six time zones has been found to reduce peak power output and work capacity on the 30-s Wingate test [112]. The same Wingate test measures, as well as shoulder strength, were also reduced after a westward travel across seven time zones [112]. Also in the latter study, testing occurred in the morning local time.

Other studies, however, report that eastward travel does not necessarily impair performance, and in some cases, travelling eastwards seems to be to the athletes' advantage. US West Coast teams travelling eastwards to meet their US East Coast opponents seemed to have an advantage during Monday Night Football games, as they won more often and by more points per game, as well as doing better than the point spread [113]. The authors noted that these games are played at 21:00 h Eastern Time, which means that West Coast teams play these games essentially at 18:00h according to their local time (whether playing home or away), and thus have an advantage of playing closer to the time of day where peak performance occurs [113]. A similar trend was found in a study of eight seasons of the US National Basketball Association. Teams travelling from the West Coast to meet an East Coast team tended to do better than teams travelling from the East Coast to meet a West Coast team. The authors noted that most games played in the league are night games, which may account for the West Coast team advantage [114]. An analysis of win-loss records for ten seasons of National Football League indicated that West Coast teams seem to have a slight disadvantage during day games played in different time zones, but an advantage during night games, both when playing at home and when playing away [115]. During ten seasons of the Major League Baseball, each team's circadian time was recorded, based on the number of time zones crossed, direction of travel, and time at the destination for resynchronization. Teams with a circadian advantage (i.e., closer to resynchronization than their opponent) won more often, and a large circadian advantage resulted in a higher winning percentage than a small circadian advantage [116]. Also in this study, teams travelling east did better. The authors did not report on the game times, nor on the differences in basic achievements between the teams (e.g., point spread). In a study of Australian Rule Footballers, no effect of travel up to two time zones was found on individual performance (measured by player statistics and coach rankings), although it is possible that there would have been an effect of travel on team performance [117]. However, travel across up to three time zones had no effect on team performance in the National Hockey League [118]. A study on teams' interstate travel in the Australian National Netball Competition found no significant effect on performance either, but the effect size of the points difference (home margin−away margin) when comparing a two-h time zone shift with no time zone shift or one-h time zone shift was large or moderate (i.e., travel across two time zones yielded greater points difference) [119]. In sum, the notion of impaired performance after eastward travel seems to be generally supported, although only when the local time of testing does not result in a body clock closer to the time of peak performance. Westward travel also seems to produce impaired performance, but whether this effect is smaller than that of eastward travel is not easy to determine due to differences between study protocols [112].

The local time of measurement in the aforementioned studies varied from early morning [111] to close to midnight [113] and seems to reflect natural variations in times for athletic competitions. Whether impaired performance following time zone travel is mediated by direct circadian effects on performance or through impaired sleep is difficult to say as only one study specifically assessed sleep in the travelling athletes. In that study, sleep was not associated with performance [117]. Impaired performance following travelling may also be related to stress, restricted motion, and altered diet [119].

Discussion

We identified a relatively small number of studies investigating the effect of sleep duration on athletic performance. Sleep deprivation was found not to influence performance in a number of studies [6,8–11,13,23], most of which measured short-term performance with a considerable anaerobic component. However, a large number of the studies observed a decrease in performance after sleep deprivation or recovery from sleep deprivation [14–22], many of which measured endurance performance. It is likely that psychological effects (e.g., motivation) contribute to the adverse effect of sleep deprivation upon endurance performance [20]. This proposed mechanism is in line with theoretical notions concerning motivation as a mediator of the effects of sleep deprivation [120]. Sleep deprivation seems to influence evening performance to a greater extent than morning performance [7,20,25]. The reduced evening performance is likely a result of lower circadian rhythm amplitude after sleep deprivation [7,121]. Only a minority of the studies on total sleep deprivation measured performance in the evening [7,20], a limitation which may have led to fewer significant results. Regarding partial sleep deprivation, depriving sleep only in the beginning of the night seems not to reduce performance [6,24,25], although the contrary is reported for partial sleep deprivation over several days, probably because this leads to accumulation of sleep debt and fatigue as well as elevation of perceived exertion [27].

Most of the studies investigating sleep deprivation had fewer than 20 subjects. Power calculations were not reported in the vast majority of studies. Due to low statistical power, there is a certain possibility that the effect of sleep deprivation is underestimated. The fact that extending sleep for several weeks [29] and napping when having a sleep debt [28] are related to improved performance further suggests that sleep duration is of importance for athletes. Napping is likely beneficial whether it is of short or longer duration, that is, whether or not it includes deep sleep, provided the athlete has time to overcome sleep inertia [2].

There is ample evidence attesting to the effect of time of day on performance. The vast majority of these studies report that performance increases from morning to afternoon or evening. Sports involving technical skills (e.g., badminton, tennis, soccer) seem to have an acrophase somewhat earlier in the day (i.e., in the afternoon) [30,31,33] than that of muscle strength and anaerobic performance, which seems to peak in the early evening [51,61–63,66,81,82]. Technical skills involve fine motor control to a greater extent, and this is known to peak earlier in the day [2]. In general, cognitive and sensory-motor components in different performances are more affected by the time awake than gross motor movements [122]. If we had not excluded sports which involve mainly coordination (e.g., shooting) the number of studies reporting an earlier acrophase in performance might have been higher. There are indications that diurnal variations may be moderated by several factors. Increasing body temperature by being in warm surroundings may reduce or eliminate this diurnal variation [57,59,60], or produce a diurnal pattern where performance is better in the morning [102], although increasing body temperature through conducting a thorough warm-up has not consistently been found to be effective [53,67,74,87,94]. In one study, doubling the warm-up in the morning raised body temperature to evening levels, but this did not improve swimming performance. This was possibly due to muscle fatigue (failure to

recover from the thorough warm-up) [87]. Furthermore, it seems that regular exercise in the morning may be able to improve morning performance relative to evening performance [48,49,88,104], although the results are not conclusive [86]. Sleep deprivation is another factor which may decrease the diurnal variation in performance, through reduced evening performance, especially after total sleep deprivation or when sleep deprivation occurs in the last part of the night [7,20,25].

In terms of circadian desynchronization, the sum of small changes in individual performance may produce significant changes in team performance [117]. West to east travel is associated with impaired athletic performance [107–109,111,112]. However, others find that individual performances do not decrease after eastward travel (although this may be due to low statistical power) [110]. Performance may indeed be enhanced after eastward travel when travelling athletes have a circadian advantage due to the time of the competition (e.g., very late at the destination) [113–116]. Westward travel has also been found to decrease performance [112]. Overall, when evaluating the impact of crossed time zones the competition time relative to the athletes' biological time must be considered.

Methodological issues

Apart from the small sample sizes already noted, other methodological issues deserve mention. Some of the studies on sleep and diurnal variation included strict protocols where diet (e.g., consumption of food, liquid and stimulants), activity level, and environmental conditions (e.g., room temperature, light conditions and equipment) were controlled [e.g., [7,17,25,79]], while others had less control over these potentially confounding variables. Studies also varied concerning control over sleep, and time of day; some studies assessed performance at very specific times [e.g., [36,46,51,83,85]] whereas others operated with a rather wide window in which the performance was conducted. Some of the studies utilized a counterbalanced design, and were thus able to control for possible learning effects [e.g., [11,18,24,56]], other studies did not. Similarly, some of the studies have taken into consideration circadian preferences (morningness–eveningness) by including only one "chronotype" [e.g., [30,33,34,47,55,58,67,71,76]]. Others have not taken circadian preferences into consideration to the same extent. Most studies include only male subjects, however, a number of studies have mixed samples without taking into account gender differences or the females' menstrual phase [e.g., [31,32,39,50,56–58,61,123]]. The choice of subjects' physical condition or level of expertise may also influence the result. Some of the studies were conducted on highly motivated professional athletes, who were competing in games or against each other, probably having high levels of motivation [e.g., [11,29,56,78,82,110]]. In contrast, other studies were conducted on untrained individuals, where the variation in motivation among the individuals may have been larger. Age may also be a relevant factor to take into consideration in terms of the effects of sleep and circadian rhythm on athletic performance.

Many of the studies on diurnal variation have only measured performance at two time points across the day, and thus only provide a very crude evaluation of the circadian effect on performance. Other studies have measured performance more frequently and are thus useful for drawing detailed inferences about circadian effects on performance. The latter type of study tends to support the notion of a performance peak in the afternoon or evening [e.g., [33,35,36,39,40,51,55,61,62,66,81,83,85]]. By using cosinor analyses, some authors have estimated specific times for performance acrophase [e.g., [62,63,81]].

There is variation across studies regarding the time for recovery allowed for the subjects between the test sessions; some authors have measured performance several times on the same day [e.g., [50,52]] while most have included a recovery period of one or several days in order to avoid fatigue effects.

The studies on desynchronization of circadian rhythms on team performance take advantage of archival data, and are thus based on a large data corpus. Still, these are field studies where important factors are not controlled for, such as sleep and other possibly important factors. Some of the studies have taken into account important factors like point spread [113], the teams' winning records [114], local time of playing [113–115], comparison of pairs of games [119], or the teams' travel schedules throughout the season (i.e., adjusted for present circadian times at the time of competition) [116].

Some types of athletic performances are not represented in the literature. For instance, we found no studies which investigated outdoor winter sport performance. Research on outdoor sports also encounters additional potential confounders in the form of climate variables. Fighting sports (e.g., boxing, judo, or wrestling) are not studied either. Individual performance in a team is investigated to some extent, but the interplay among team members, which is very relevant for team performance, is not focused on.

When investigating athletic performance, it is not easy to isolate the specific motoric skills comprising the performance, especially in sports involving complex technical skills. It is also a challenge to isolate the motor or physical skills from cognitive functioning, mood or motivation required for the task at hand, which may also be influenced by sleep deprivation or circadian factors.

Recommendations for future studies

There are numerous challenges in designing studies that investigate the effect of sleep deprivation and circadian rhythms on athletic performance. Future studies should consider several important methodological issues. First, power calculations should be computed to ensure that the sample is large enough to detect differences in performance between study conditions. Second, studies based on repeated measures design should be counterbalanced and incorporate sufficient time for recovery between consecutive tests of performance. Third, studies should include a strict protocol, where potential confounders should be controlled for. To study the effect of circadian rhythms on performance, a protocol with an ultra-short sleep–wake cycle is preferable [85]. To study the effect of sleep loss, partial sleep deprivation should be used instead of total sleep deprivation, both to make the study more relevant to real world competitions and to make participation somewhat less demanding for the subjects. Potential interaction effects between sleep loss and time of day on performance should be addressed. Future studies on the effects of sleep deprivation on muscle performance should be designed so that the effects on single muscles output can be differentiated from the effects on muscle groups (the latter demanding more neuronal coordination than the former).

Conclusion

Although a night of poor sleep and a suboptimal time of day are not always detrimental to performance, a good night's sleep and an inner body clock tuned to evening time are important factors for athletes determined to perform their very best. Optimal premises are especially important in professional sports where the margins are small between success and failure, and the stakes are high.

Practice points

- There is mixed evidence that sleep deprivation influences athletic performance. Tasks requiring short-term high-power output seem largely unaffected, while endurance performance seems to decrease after sleep deprivation.
- The influence of desynchronization of circadian rhythms due to travel depends on the local time the competition/game unfolds, relative to the individual's biological time.
- Performance is better in the afternoon or evening than in the morning for nearly all kinds of sports demanding physical skills. Technical performance may peak somewhat earlier in the day than skills demanding more power. Being in warm surroundings may moderate this effect.

Research agenda

There is a need for studies which:

- Investigate the magnitude of partial sleep deprivation needed to produce negative effects on athletic performance.
- Investigate athletic performance in people with different circadian preferences (morningness–eveningness) and exercise habits.
- Investigate the moderating effects of warm-up and climate on the circadian effects on performance.
- Control for several potential confounders (chronotype, diet, training regime, climate, sleep and time of day).
- Have sufficient statistical power.

Conflicts of interest

The authors report no conflict of interests.

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